Synthesis and mass determination of heavy and superheavy nuclei at separator VASSILISSA

A.V. Yeremin[1], Y.T. Oganessian[1], A.G. Popeko[1], O.N. Malyshev[1], A.V. Belozerov[1], V.I. Chepigin[1], M.G. Itkis[1], A.P. Kabachenko[1], R.N. Sagaidak[1], A.V. Shutov[1], A.I. Svirikhin[1], S. Hofmann[2], S. Saro[3]

[1] Joint Institute for Nuclear Research, Russia
[2] Gesellschaft fuer Schwerionenforschung, Germany
[3] Comenius University, Slovak Republic

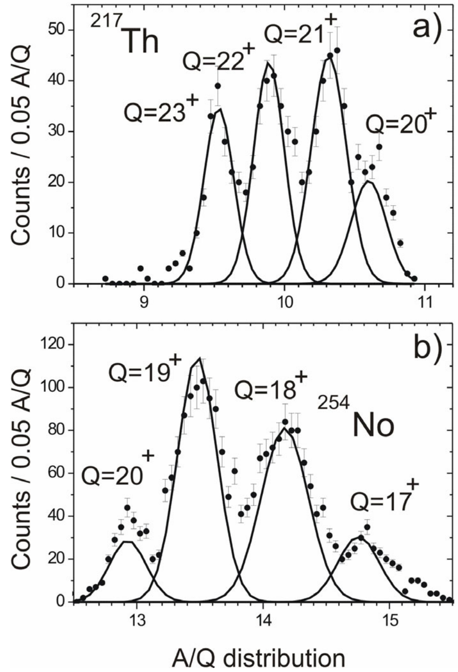
eremin@sunvas.jinr.ru

One of the criteria of the quality and reliability of the experimental results in the field of the synthesis of superheavy elements (atomic number $Z \geqslant 110$) is the reproducibility of the obtained data. Because the cross section values for the synthesis of elements with $Z \geqslant 110$ are at the level of picobarns and even lower it results in possible detection of one nucleus per few weeks using the presently available techniques. Another limiting point in attempts to reproduce presently obtained results is the problem of exact reproduction of the beam energy at the half - thickness of the target. The deviation of the beam energy of 1 % (typically 2 - 3 MeV) could lead to the reduction factor of 2 - 3 and to make the recurring ineffective. Until now only few experiments could be mentioned as successful repetition of previously obtained results. First are the experiments at the velocity filter SHIP aimed to the conformation of the synthesis of the isotopes $^{272}111$ and $^{277}112$ made earlier with the use of the same experimental set-up [1]. And second are the experiments performed at RIKEN with gas filled separator GARIS successfully repeated SHIP group experiments on the synthesis of the isotope $^{271}110$ [2].

The study of the decay properties and formation cross sections of the isotopes of elements 110, 112 and 114 was performed employing high intensity ^{48}Ca beams and ^{232}Th, ^{238}U, ^{242}Pu targets [3,4,5] and the electrostatic separator VASSILISSA [6] during the years 1998 - 1999. At beam energies corresponding to the calculated cross section maxima of the 3n evaporation channels the isotopes $^{277}110$, $^{283}112$ and $^{287}114$ were produced and identified (see also [7]).

Aiming at the continuation of the experiments on the synthesis and study of decay properties of superheavy nuclei with the use of accelerated ^{48}Ca beams and at the increasing the identification ability of the experiments the separator VASSILISSA was upgraded. For that purpose a new dipole magnet, having a deflection angle of 37 degrees, was installed behind the separator VASSILISSA replacing the old 8° magnet. The new magnet provides an additional suppression of unwanted reaction products and a possibility to have the mass resolution at the level of 1.5 -2 % for heavy nuclei with masses of about 300 amu.

The VASSILISSA separator with the new dipole magnet was tested with a number of heavy ion induced complete fusion reactions [8,9]. The evaporation residues produced in reactions of ^{40}Ar bombarding ions with ^{164}Dy and ^{208}Pb targets and of ^{44,48}Ca ions with ^{174}Yb, ^{198}Pt, ^{204,206,208}Pb targets were used in the analysis. Using ER - α and ER - SF correlation analysis for detected ER's TOF and strip number (that corresponds to the certain value of Bϱ) were evaluated. Together with known value of magnetic field B of magnetic analyzer it was possible to evaluate A/Q values and for known A the charge distributions for investigated nuclei can be extracted. The results obtained for A/Q distributions of the ^{217}Th and ^{254}No ER’s are shown in the following figure.



The first planned experiment in the field of superheavy elements with the use of upgraded separator was aimed to the synthesis of the isotope $^{283}112$. It was the first experiment with ^{48}Ca beams in 1998, focused to the synthesis of heaviest elements, and it became the basis for all other search experiments for synthesis elements with Z=114 - 118. An additional reason was the fact that the non-observation of any events in the reaction $^{48}Ca + ^{238}U \rightarrow ^{283}112^*$ studied with the BGS separator at Berkeley at the beam energy $E_{1/2}$ =231 MeV in the half - thickness of the target was reported in [10].

Enriched ^{238}U (99.999 %) material was used for the preparation of the targets. The projectile energy was varied by extracting the beam from an appropriate radius of the cyclotron. The beam energy was determined by measuring the energy of the ions scattered at 30^0 in a thin (200 μg/cm^2) Au foil and with a time-of-flight technique. Beam energy values measured by both methods coincide within an interval of ± 1 MeV (± 0.5 %). An accuracy of the determination of the beam energy absolute value was tested using a magnetic spectrometer MSP144 and was about 0.5 % at the level of 243 MeV. The measured energy spread of the scattered ions was 1 % (FWHM).

At a beam intensity of $4 \cdot 10^{12}$ ions·s^{-1}, the total counting rate of all events at the focal plane detectors was 5 - 10 s^{-1}. The counting rate at a single strip in a position interval of 1.0 mm amounted to the following values; for the α - like signals (in the absence of signals from the TOF detectors) with an energy higher than 5.5 MeV - less than 0.075 h^{-1}; for the α - like signals with an energy of 0.5 - 5 MeV (signals corresponding to escaped α particles) - about 0.2 h^{-1}; for recoil - like (ER - like) signals (with a TOF signal) with an energy higher than 5 MeV and time of flight corresponding to heavy ER's (70 - 90 ns) - less than 0.1 h^{-1}.

After preparatory experiments, irradiation of the U target started at the beam energy $E_{1/2}$ =230 - 231 MeV in the middle of the target, which is close to that used in the previous experiment [3]. During a period of 29 days a beam dose of $5.91 \cdot 10^{18}$ projectiles was collected. No SF events were detected during this irradiation. In addition, possible decay chains of the ER $\rightarrow \alpha \rightarrow \alpha 1 \rightarrow \alpha 2$ type were searched for within time intervals 5 μs < t < 1000 s and 8 MeV < E_α < 13 MeV. Signals from α decay could be missed only in the case when an α particle escaped through the open front side of the detector array (30 % probability) or when the lifetime was shorter than 2 μs and the decay occurred in the dead time of the data acquisition system. The windows for the relative positions were twice as much as the resolution at FWHM. No such decay chains were found for the irradiation at the beam energy $E_{1/2}$=230 - 231 MeV. The upper cross-section limit obtained at this energy is 2.25 pb at a probability level of 68 %.

Then the energy of bombarding ions was increased up to $E_{1/2}$=234 MeV, resulting in the excitation energy of the compound nucleus ^{286}112 E*=35 MeV. During a period of 15 days a beam dose of $4.68 \cdot 10^{18}$ projectiles was collected. Two events from spontaneous fission were detected in this irradiation at the higher beam energy. Both SF events were characterized by a coincident event of higher energy signals (52 and 130 MeV) in the stop detector and lower energy signals (13 and 40 MeV) in the backward detectors. Correlation analysis of the possible decay chains of the ER $\rightarrow \alpha \ldots \rightarrow$ SF type with the upper limit of the time intervals t of up to 10,000 s resulted in two ER - SF correlations. The position difference determined from the ER and SF signals was 0.6 mm for the first event and 0.8 mm for the second one. Time intervals ΔT=180.5 sec and 1459.5 sec., respectively, were measured. The probability that the first correlation is a chance event is 0.005, for the second SF-event the corresponding probability is 0.038.

We attempted to identify SF activities observed in the ^{48}Ca + ^{238}U reaction using mass determination with the 37° dipole magnet. Using ER - SF correlations, positions of the implanted ER's and corresponding TOF's were extracted. The most probable atomic mass values for the most probable charge states were found by solving a system of equations for A/Q values by the maximum likelihood method. For the first event a corresponding ratio A/Q=16.0 and for the second one A/Q=16.679. The values A=288.0 (Q=18) and A=283.5 (Q=17) for the first and second events were obtained. We estimated the accuracy of mass measurements to be about 2 %. Mean value of the masses for two detected nuclei amount <A> 285.7 ± 5.7. Cutting down the upper limit by the mass of compound nucleus A_{CN}=286, mass interval from A=280 to A=286 could be obtained. This result indicates, first of all, that the observed nuclides belongs to the region of superheavy nuclei and their masses are close to the expected masses of the evaporation products of the reaction ^{48}Ca + ^{238}U. Due to the relatively low excitation energy of compound nucleus $E_{CN}^* \approx 35$ MeV the evaporation of charge particles (protons or α particles) is strongly prohibited, more probable that the events measured in this work belongs to the isotope ^{283}112 produced via a 3n evaporation channel in the reaction ^{48}Ca + ^{238}U $\rightarrow$ ^{286}112*.

The mean value of the two measured time intervals together with four previously measured events [3,4] results in a half-life $T_{1/2} = 307^{+212}_{-89}$ s which coincides well within error bars with reported earlier values [3,4]. The cross-section evaluated for the production of two fission events at a beam energy of 234 MeV in the half-thickness of the target is 3^{+4}_{-2} pb that coincides well in error intervals with reported earlier values obtained with the separator VASSILISSA [3] (5^{+6}_{-3} pb) and in the experiment aimed at the determination of chemical properties of element 112 performed at Dubna in 2001 [11], were 8 SF events were detected, that corresponded to the cross-section $2^{+0.9}_{-0.7}$ pb. In February - March 2003 the experiment aimed to the determination of chemical properties of element 112, synthesized in the reaction ^{48}Ca + ^{238}U, was performed at GSI Darmstadt [12]. Few SF events were detected that corresponded to the cross-section in the range of 1 – 5 pb and is in good agreement with results, obtained with VASSILISSA separator and chemical experiment at Dubna.

The deviation of the beam energy value at which the events were obtained during this experiment and the reported 5 years ago value [3] could be explained by the fact that an accuracy of the absolute values of beam energy measurements 5 years ago was not tested and deviations could be at the level of 1 - 1.5 %, i.e. 2.5 - 3.5 MeV, and/or by the fact that in the past experiment 1.6 mg/cm^2 Al backing foils were used for the target support (about 25 MeV energy losses for ^{48}Ca beam with an energy of about 5 A·MeV) whereas now 0.74 mg/cm^2 Ti backing foils were used (about 10 MeV of energy losses).

The obtained results of mass measurements of heavy ER's allow one to exclude transfer products and incomplete fusion products and to assign the two observed SF events to the complete fusion of ^{48}Ca + ^{238}U with a high probability. The non-observation of α decay, the improbable evaporation of protons or α particles from the compound nucleus and the relatively low excitation energy of 35 MeV let us assign the fission events measured in this work to the isotope $^{283}112$ produced via the 3n evaporation channel in the reaction $^{48}Ca + ^{238}U \rightarrow ^{286}112^*$.

The non-observation of any events in the reaction $^{48}Ca + ^{238}U \rightarrow ^{286}112^*$ at the beam energy $E_{1/2}$ =231 MeV [8] can be explained by the fact that the beam energy was too low and corresponded to the left side of the excitation function, in which a decrease in the cross section value is very sharp.

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References

[1] S. Hofmann, F.P. Hessberger, D. Ackermann, G. Muenzenberg, S. Antalic, P. Cagarda, B. Kindler, J. Kojouharova, M. Leino, B. Lommel, R. Mann, A.G. Popeko, S. Reshitko, S. Saro, J. Uusitalo, A.V. Yeremin, Eur. Phys. J. A14, 147 (2002)

[2] K. Morita, K. Morimoto, D. Kaji, A. Yoneda, A. Yoshida, T. Suda, E. Ideguchi, T. Obnishi, Y.L. Zhao, H. Xu, T. Zheng, H. Haba, H. Kudo, K. Sueki, A. Ozawa, F. Tokanai, H. Koura, A.V. Yeremin, R. Kanumgo, K. Katori, I. Tanihata, RIKEN Accel. Prog. Rep. 35 (2002)

[3] Yu.Ts. Oganessian, A.V. Yeremin, G.G. Gulbekian S.L. Bogomolov, V.I. Chepigin, B.N. Gikal, V.A. Gorshkov, M.G. Itkis, A.P. Kabachenko, V.B. Kutner, A.Yu. Lavrentev, O.N. Malyshev, A.G. Popeko, J. Rohac, R.N. Sagaidak, S. Hofmann, G. Muenzenberg, M. Veselsky, S. Saro, N. Iwasa, K. Morita, Eur. Phys. J. A5, 63 (1999)

[4] Yu.Ts. Oganessian, A.V. Yeremin, A.G. Popeko, S.L. Bogomolov, G.V. Buklanov, M.L. Chelnokov, V.I. Chepigin, B.N. Gikal, V.A. Gorshkov, G.G. Gulbekian, M.G. Itkis, A.P. Kabachenko, A.Yu. Lavrentev, O.N. Malyshev, J. Rohac, R.N. Sagaidak, S. Hofmann, S. Saro, G. Giardina, K. Morita, Nature 400, 242 (1999)

[5] Yu.Ts. Oganessian, A.V. Yeremin, A.V. Belozerov, M.L. Chelnokov, V.I. Chepigin, V.A. Gorshkov, A.P. Kabachenko, S.P. Korotkov, O.N. Malyshev, A.G. Popeko, J. Rohac, R.N. Sagaidak. S. Hofmann, G. Muenzenberg, M. Veselsky, S. Saro, N. Iwasa, K. Morita, G. Giardina. in: Proc. of the Int. Workshop on "Fusion Dynamics at the Extremes", Dubna, Russia, 25--27 May, 2000, Editors Yu.Ts. Oganessian, V.I. Zagrebaev (World Scientific, Singapore, 2001) 81.

[6] A.V. Yeremin, D.D. Bogdanov, V.I. Chepigin, V.A. Gorshkov, A.P. Kabachenko, O.N. Malyshev, A.G. Popeko, R.N. Sagaidak, G.M. Ter-Akopian, A.Yu. Lavrentjev, Nucl. Instr. Meth. B126, 329 (1997)

[7] A.V. Yeremin, A.V. Belozerov, M.L. Chelnokov, V.I. Chepigin, V.A. Gorshkov, A.P. Kabachenko, O.N. Malyshev, Yu.Ts. Oganessian, A.G. Popeko, R.N. Sagaidak, A.I. Svirikhin, S. Hofmann, G. Berek, I. Brida, S. Saro, in: Proc. of VII Int. School-Seminar on Heavy Ion Physics, 27 May - 1 June, 2002, Dubna, Russia; To be published in Yad. Fiz. (Phys. At. Nuclei) 66 (2003)

[8] A.V. Belozerov, M.L. Chelnokov, V.I. Chepigin, T.P. Drobina, V.A. Gorshkov, A.P. Kabachenko, O.N. Malyshev, I.M. Merkin, Yu.Ts. Oganessian, A.G. Popeko, R.N. Sagaidak, A.I. Svirikhin, A.V. Yeremin, G. Berek, I. Brida, S. Saro, Eur. Phys. J. A16, 447 (2003)

[9] O.N. Malyshev, A.V. Yeremin, A.G. Popeko, A.V. Belozerov, M.L. Chelnokov, V.I. Chepigin, V.A. Gorshkov, S. Hofmann, M.G. Itkis, A.P. Kabachenko, Yu.Ts. Oganessian, R.N. Sagaidak, S. Saro, A.V. Shutov, A.I. Svirikhin, Submitted to Nucl. Instr. Meth. A.

[10] W. Loveland, K.E. Gregorich, J.B. Patin, D. Peterson, C. Rouki, P.M. Zelinski, K. Aleklett, Phys. Rev. C66, 044617 (2002)

[11] A.B. Yakushev, I. Zvara, Yu.Ts. Oganessian, A.V. Belozerov, S.N. Dmitriev, B. Eichler, S. Huebener, E.A. Sokol, A. Tuerler, A.V. Yeremin, G.V. Buklanov, M.L. Chelnokov, V.I. Chepigin, V.A. Gorshkov, A.V. Gulyaev, V.Ya. Lebedev, O.N. Malyshev, A.G. Popeko, S. Soverna, Z. Szeglowski, S.N. Timokhin, S.P. Tretyakova, V.M. Vasko, M.G. Itkis, Preprint JINR E12-2002-297, Dubna 2002. Submitted to Radiochimica Acta
[12] H. Gaeggeler, In: Proc. of VIII Int. Conf. "Nucleus - Nucleus Collisions", June 17 - 21, 2003, Moscow, Russia; To be published in Nuclear Physics.